FUTURE HADRON SUPER COLLIDERS:
THE FARTHEST ENERGY FRONTIER

WILLIAM A. BARLETTA

E. O. Lawrence Berkeley National Laboratory, Berkeley CA 94720

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Abstract

Advances in superconducting materials and magnets, in accelerator physics, and in beam feedback, control and instrumentation systems allow us to consider the practical design of a proton collider with a discovery potential well beyond that of the Large Hadron Collider (LHC) currently being constructed at CERN. The ELOISATRON (ELN) (or Very Large Hadron Collider (VLHC)) represents what may well be the final step on the energy frontier of accelerator-based high energy physics. Despite the existence of detailed designs of the SSC (at 20 TeV per beam), more than 15 years of technical studies[1] for an ELOISATRON (ELN) at 100 TeV per beam, and an extensive study[2] of a Very Large Hadron Collider (VLHC) at FNAL, the economic practicality of a collider at 50 to 100 TeV per beam will remain uncertain until appropriate arc dipole designs have been tested in model magnet configurations. A vital step toward an affordable ELN is research now underway aimed at the upgrade of the Large Hadron Collider (LHC) at CERN.

1 Overview

In the broadest sense, the ELN is the ultimate femtoscience experiment in that it explores phenomena that were commonplace during the first 100 femtoseconds of the universe. In more programmatic parlance the ELN represents a program for 50 years of forefront, high energy physics. Its characteristics are the following:

1) It is a large advance beyond LHC. In fiscal terms, multi-step construction scenarios seem to be the most realistic. Eventually the full ELN with more than 100 TeV per beam would be achieved using multiple rings occupying the same tunnel.
2) No extraordinary technical difficulties preclude ELN at 10^{35} $cm^{-2}s^{-1}$ with present technologies. However, radiation damage to detectors and interaction region components is a serious issue requiring more investigation.
3) The discovery potential of ELN far surpasses that of lepton colliders in that ELN combines a much higher energy with high luminosity.
4) At present a super LHC leading to an ELN is *the only sure way* to

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[1] See for example, "Supercolliders and SuperDetectors," W. A. Barletta and H. Leutz, editors, World Scientific, 1993 and "Hadron Colliders at the Highest Energy and Luminosity," (Proceedings of the 34th Workshop of the INFN Project," Erice, Italy 4-13 November, 1996), A. G. Ruggiero (ed.), World Scientific, 1996

[2] "Design Study for a Staged Very Large Hadron Collider, " Fermilab-Report TM-2149, June 1, 2001. Hereafter VLHC Study

access the energy scale >1 - 10 TeV In fact, proton synchrotrons could reach up to 1 PeV proton c.m. energy, if a way to operate with a warm bore vacuum system can be developed.

During the past several years the ELN program of workshops and detector development in Europe has been complemented by the VLHC research effort in the US. That effort is the product of a loose collaboration formed in 1998 by Fermilab, LBNL and Brookhaven to investigate the development of a post-LHC hadron collider sited at Fermilab. VLHC Design Study produced by the collaboration represents the most detailed examination of the physics and technology issues relevant to an ELN or VLHC.

2 Accelerator Physics Issues

From its outset the VLHC collaboration has considered three diverse design strategies for realizing the VLHC. The first strategy is a low field approach (LF) using 2 T superferric magnets excited by a superconducting transmission line. This approach requires a tunnel > 200 km in circumference to reach 20 TeV per beam and results in extremely large stored beam energy. Even at 20 TeV, synchrotron radiation has minimal influence on machine design. A second approach, which has received minimal detailed study, is based on using ductile NbTi superconductor in a dual aperture RHIC-like magnet design operating at 4 - 6 T. This option offers some limited luminosity enhancement from radiation damping. The third option (HF) employs high field magnets with brittle, Nb_3Sn superconductor operating at >10 T. This approach minimizes both the size of the tunnel, and the stored beam energy, but maximizes the consequences of synchrotron radiation.

Accelerator physics issues relevant to all three approaches were reviewed at SLAC in March 2001 at the VLHC Instability Workshop[3]. The most serious potential difficulty identified is the transverse mode coupling (TMCI) instability. The TMCI is driven by the numebr of particles in a bunch, N_{beam}. The TMCI safety factor, $N_{threshold} / N_{beam}$ is 0.5 for the low field case and 8 for the high field case. The low field case is not, however, ruled out as this estimate is likely to be pessimistic. Moreover, the instability can likely be controlled by feedback systems. As the transverse coupling impedance scales with the inverse cube of the aperture[4], this instability is a critical consideration in setting the aperture of the collider. With respect to the resistive wall multi- bunch instability the growth increments are LF ~ 1 turn and HF ~ 5 turns. Work in support of the VLHC Study[5] indicate that this

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[3] www.slac.stanford.edu/~achao/ VLHCWorkshop.html
[4] The beam tube aperture has a strong effect on the cost of the arc dipole magnets in the collider. Therfore, one endevours to have the aperture as small as practical.
[5] VLHC Study, Chapter 4 and V. Lebedev, “Control of Transverse Multibunch Instabilities in the First Stage of the VLHC,” www-bdnew.fnal.gov/pbar/organizationalchart/ lebedev/VLHC/InstabilitiesAndFeedback.pdf

instability can be controlled to small amplitude with audio frequency, “feed-ahead” electronics even when the aperture of the beam tube is so small that the uncorrected growth time for the instability is less than one turn. The residual transverse motion of the beam can then be damped to microscopic values with the bunch-by-bunch feedback system that suppresses the coupled bunch modes.

Another consideration that strongly influences the choice of aperture is the loss of beam halo particles due to dynamic aperture effects induced by field errors. Among the techniques proposed to minimize this consideration is the four-aperture magnet proposed by Gupta, which eliminates the need to keep the beam at the low injection energy for an hour or more. One might also implement radially resolved, stochastic cooling[6] of the beam halo either at optical frequencies or with special, higher order mode, rf- pickup and kicker cavities. Both these approaches require extensive experimental verification. In studies of magnets for ELN and VLHC, we assume that some approach to controlling beam halo will be successful and that a magnet aperture[7] of 40 mm will be acceptable from the accelerator physics point of view. Several issues are not expected to be serious: the electron cloud instability with growth times LF – 0.25 s and HF – 0.5 - 10 s; the longitudinal microwave instability (safety factor 20); the coherent synchrotron tune-shift (safety factor ~10). Effects of ground motion can be suppressed by feedback.

For an ELN with dipole magnets with fields in excess of 6 T the production and handling of synchrotron radiation from the beam is a dominant design consideration in the specification of the magnets and beam tube as well as in the design of the cryogenic system. As the beam radiates X-rays and its emittance is reduced (via radiative cooling), the luminosity of the collider increases until the population of particles in the bunches is reduced significantly due to the collsions at the high luminosity interaction points. For the high energy experimentalist the figure of merit of collider performance[8] is not the peak luminosity but its average value. A recent calculation by Syphers[9] of integrated luminosity v. normalized beam emittance at injection, Fig.1, strongly suggests that most of the benefits of radiation damping of emittance in a collider operating at 50 TeV per beam are already realized for B = 11 T. Strong radiation could reduced the normalized emittance of the beam below <0.3 π mm-mrad, with the consequence that the rapid

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[6] A. Zholents, W.Barletta, S. Chattopadhyay, M. Zolotorev, “Halo Particle Confinement in the VLHC Using Optical Stochastic Cooling,” Proceedings of EPAC 2000, Vienna, Austria, http://accelconf.web.cern.ch/AccelConf/ e00/PAPERS/TUOAF102.pdf

[7] An extensive discussion of dynamic aperture considerations in the Stage 2 VLHC is presented in Chapter 3 of the VLHC design Study, Chapter 3. This study supports the idea that the arc dipole aperture can be kept as small as 40 mm. Note that the comparable value for the LHC dipoles is 55 mm.

[8] For one such discussion see F. Zimmermann, “Luminosity Limitations at Hadron Colliders,” CERN report CERN-SL-2001-009 AP and Proceedings of the 18th International Conference on High Energy Accelerators (HEACC2001), Tsukuba, Japan, March 26-30, 2001, http://conference.kek.jp/heacc2001/ProceedingsHP.html

[9] VLHC Study, Chapter 3

decrease of beam lifetime due to intra-beam scattering could require that the collider employ beam heating mechanisms to prevent the emittance from decreasing too much.

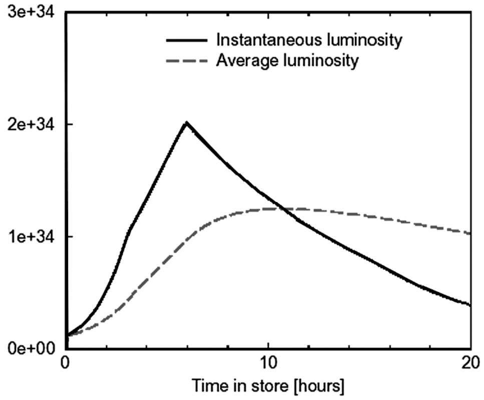

Figure 1. Evolution of instantaneous and time average luminosity during a store

In addition, radiation alters the beam distribution and the allowed tune shift consistent with acceptable backgrounds. Even at 100 TeV/beam in the high field design, the damping decrement is $<10^{-6}$. The maximum total tune shift is limited to <0.02.

The synchrotron radiation that strikes the inner surface of the beam tube deposits power that must be removed and thus limits the beam current due to three effects:

1) Direct heating of walls which leads to cryogenic heat load,
2) Indirect heating of the walls via two stream effects (electron cloud) which may triple or quadruple the heat load,
3) Photodesorption of gas that may lead to beam-gas scattering which could lead to a magnet quench.

Controlling these effects increases costs. Note that the direct thermal effects of synchrotron radiation scale with the radiation power (as the fourth power of E_{beam}) while the two-stream effects scale as the photon number (linearly with E_{beam}).

The desorbed gas molecules must be pumped out of the beam path. The mechanism used in the LHC to control deliterious radiation effects is a “beam screen” which sits within the beam tube and takes up some of the aperture of the magnet. The screen must be thick enough to stop almost all of the power carried off by the radiation. For a collider operating at 50 TeV per beam, the critical energy of the photons is a few keV; a couple of millimeters of stainless steel will be effective in absorbing the radiation. As the beam energy rises to 100 TeV as in the ELN, the critical energy of the photons increases an order of magnitude. Preventing scattered photons from depositing significant energy outside the beam screen is an issue that requires quantitative numerical simulation. Replacing the beam energy lost per turn is easily accomplished by the rf-system, the size of which is determined by the requirement that the beam be quickly accelerated from its injection value to its full design value.

Thermal loads and photo-desorption of gas in the beam tube directly drive the design of the vacuum and cryogenic systems in the collider. The beam screen improves the Carnot efficiency of the cryosystem by providing the critical function of intercepting the thermal load at a temperature (~20 K) well above the magnet temperature (2 – 4 K). The screen however increases required magnet aperture. Slots in the screen pump photodesorbed gas from the path of the beam for absorption behind the screen. This gas may be removed by 1) physical absorption by a zeolyte, which will require frequent regeneration at 20 K, 2) chemical absorption in a getter material, which has a finite life and which will require regeneration at 450 K at least annually, or 3) if the magnets operate at 2 K, by cryosorbtion on the inner bore of the magnet. An alternative approach that requires further study is to let the photons escape from the beam tube to strike small "fingers" at 70 - 100 K temperature protruding into the beam tube or to escape into an ante-chamber.

The LHC tunnel cryogenic system has more than 1 valve per magnet average. Such superfluid systems are impractical at the scale of VLHC. Generally one concludes that scaling the LHC approach to cryogenic systems is not an option.

3 Magnet Technology For ELN

SSC experience (Table 2) shows us the cost drivers for the ELN. The main collider accounted nearly 60% of costs[10]. Of this more than 80% was devoted to the collider dipoles. At fields higher than 6.7 T (the SSC baseline) this fraction is likely to be even higher. The conclusion one draws is that lowering dipole cost (per T-m) is critical to controlling the cost of hadron supercolliders.

The historical data[11] of figure 2 illustrate that for NbTi dipoles, the costs of superconductor are a substantial fraction of the total magnet costs. While conductor cost remains the primary issue for Nb_3Sn magnets, we must also lower other cost components with particular attention paid to assembly costs in order to lower the magnet cost per T-m. While the construction of ELN is far in the future and the conductor, we must begin a vigorous campaign now to develop cost reduction strategies.

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[10] "Report on the Superconducting Super Collider Cost and Schedule Baseline," DOE/ER-0468P, January, 1991.

[11] Steven Gourlay, Private communication, 2001. Note that at present the cost of high quality Nb_3Sn is five time the cost of NbTi. We assume that the cost per kA-m of Nb_3Sn will drop a factor of five to that of NbTi once the size of the metal billets is scaled to hundreds of kilograms. Historically this scaling of conductor cost with billet size was the case for NbTi.

Recent advances in the design of Nb_3Sn magnets at LBNL demonstrate that one can consider arc dipoles in the field range of 11-15T for a future collider. Although choosing lower fields will result in less costly magnets, it is far from obvious that the least expensive magnet will result in lowest cost collider. Magnet development must proceed with consideration of conductor and machine issues and vice versa. Ultimately, the choice of dipole magnetic field must be determined in conjunction global optimization of other machine parameters and costs.

Collider System	**Fraction of Total SSC Collider Ring Cost**
TOTAL	100 %
Construction – Below Ground	15 %
Construction – Above Ground	5 %
All Magnets (except IR)	61 %
All Other Collider Systems	19 %

Table 2. A comparison by major system of the SSC baseline cost.

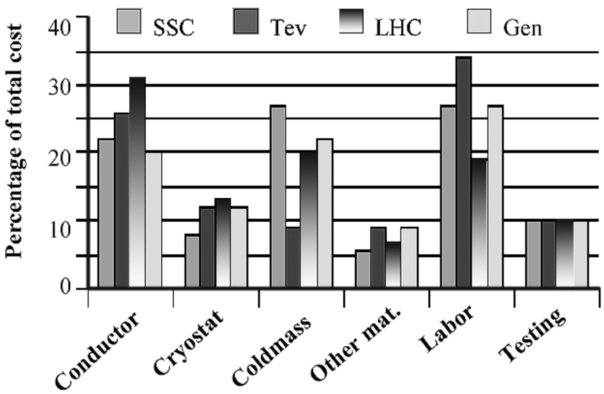

Figure 2. Estimated cost breakdown for superconducting dipoles built for SSC, the Tevatron and SSC

During the past decade a number of developments in superconducting materials and in accelerator magnet design have greatly increased our confidence in the practicality of an ELN (200 TeV) operating at a luminosity of $>10^{34}$ $cm^{-2}s^{-1}$. The technical achievements in the period from 1995 – 2003 included the following:

1. the 13.5 Tesla, D20 model magnet[12] at LBNL (55 mm aperture) and the 11.3 T, MSTU model magnet[13] at the University of Twente both made with Nb_3Sn in a cosine θ configuration,

[12] A.D. McInturff, R.Benjegerdes, P. Bish, S. Caspi, K.Chow, D. Dell'Orco, D. Dietderich, R. Hannaford, W. Harnden, H. Higley, A. Lietzke, L. Morrison, M. Morrison, R. Scanlan, J. Smithwick, C. Taylor, and J. van Oort, "Test Results for a High Field (13T) Nb3Sn Dipole, "

2. new magnet design paradigms[14] which seem to promise lower costs ($/T-m) for accelerator dipoles magnets than cosine □designs at fields in the range of 12 to 16 T,
3. demonstration of new support and pre-stress structures to facilitate magnet fabrication and permit component re-use in R&D programs,
4. commercial availability[15] of Nb_3Sn conductor with non-copper J_c >3 kA/mm^2 at 12 Tesla,
5. successful tests at LBNL of model dipoles in the common coil configuration[16] and block dipole configuration that have achieved record dipole fields of 14. 7 T and 16 T respectively,
6. production of multi-filamentary, high temperature superconductors (HTS) of BiSSCo-2212 in sufficient quantity to allow fabrication of HTS Rutherford cable and tests of this cable in small racetrack coils at Brookhaven National Laboratory,
7. development of organic insulators[17] capable of radiation resistance at levels exceeding 100 MGray,
8. initiation of a substantial collaborative program[18] to develop high gradient Nb_3Sn quadrupoles for the high luminosity interaction regions at LHC.

Improving the complex, time-consuming, and expensive design of D20 has proceeded (Fig. 3) along four interconnected paths: 1) conductor development, 2) structure improvement, 3) innovative coil geometry, and finally integrated magnet tests. The most recent success in this program is the HD-1 magnet at LBNL which employs a Nb_3Sn, block coil design and new high quality superconductor to

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Proceedings US Particle Accelerator Conference, 1997, http://accelconf.web.cern.ch/accelconf/ pac97/papers/pdf/4C007.PDF

[13] A.den. Ouden, S. Wesel, E. Krooshop, R. Dubbeldam and H.H.J. ten Kate, "An Experimental 11.5 T Nb3Sn LHC Type of Dipole Magnet," IEEE Trans. on Magnetics, v. 30, No. 4, July 1994, pp. 2320 -2323

[14] For examples see, R. Gupta, "A Common Coil Design for High Field 2-in-1 Accelerator Magnets," Proceedings of the 1997 Particle Accelerator Conference, Vol. 3, pp. 3344-3346, May 1997 and C. Battle, N. Diaczenko, T. Elliott, D. Gross, E. Hill, W. Henchel, M. Johnson, P. McIntyre, A. Ravello, A. Sattarov, R. Soika, D. Wind, "Optimization of Block-Coil Dipoles for Hadron Colliders,"

[15] The US Conductor Development Program managed by LBNLhas led to tripling of the critical current performance of Nb_3Sn wire available from industry.

[16] L. Chiesa, S. Caspi, D.R. Dietderich, P. Ferracin, S.A. Gourlay, R.R. Hafalia, A.F. Lietzke, A.D. McInturff, G. Sabbi and R.M. Scanlan, "Magnetic Field Measurements of the Nb3 Sn Common Coil Dipole RD-3c," Proceedings of the 2003 US Particle Accelerator Conference, Portland, OR (in press)

[17] K. Bittner-Rohrhofer, P. Rosenkranz, K. Humer, H. W. Weber, J. A. Rice, P. E. Fabian, and N. A. Munshi , "Characterization of Reactor Irradiated Organic And Inorganic Hybrid Insulation Systems For Fusion Magnets,". AIP Conf. Proc. 614(1) 261 (15 May 2002)

[18] The US LHC Accelerator Research Program (LARP) is a collaboration of Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (FNAL), and Lawrence Berkeley National Laboratory (LBNL), and CERN to ensure the maximum performance of LHC in support of high-energy physics. "US LHC Accelerator Research Program Proposal," http://www-td.fnal.gov/LHC/USLARP.html

achieve 16 T at 4.5 K. During this same period, complementary programs in high-field magnet development at BNL and FNAL have emphasized high temperature superconductors and cosine coil designs respectively.

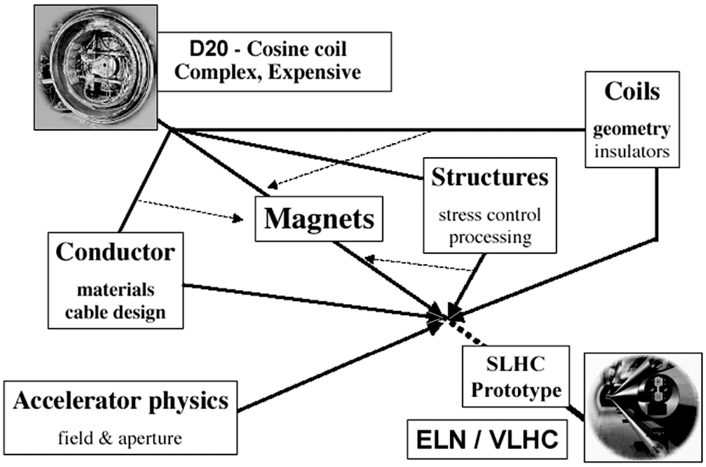

Figure 3 . Elements of an integrated research program aimed at providing cost-effective magnets for a future proton supercollider. The magnet tests (diagonal) are the proof of progress. SLHC is the LHC energy doubler.

4 VLHC Design Study

As considerable work must be done to identify the most cost-effective way of building high field magnets, and since the cost of a very large tunnel is more effectively amortized over decades of operation, the VLHC Steering Committee encouraged the development of staged deployment scenarios for the next hadron supercollider beyond the LHC. Such scenarios recognize that the next tunnel may be the last one built for high energy physics. Staged scenarios inherently look at the overall plan for high energy physics over a few decades to identify practical means of incremental improvement of the collider infrastructure. In that sense staged scenarios may be regarded as cost management strategies.

Our collaboration has envisioned several phased scenarios of building multiple machines in a large tunnel. One such staged scenario[19] was analyzed in considerable detail in the VLHC Design Study. In that scenario each stage promises new and exciting particle physics. The basic concept is to build a big tunnel, the biggest reasonable for the site. Such a tunnel near Fermilab would support a collider with 20 TeV/beam in a 233 km-circumference ring, based on a superferric, 2T transmission line magnet design[20]. The first stage VLHC assists in

[19] VLHC Study, Ch. 3.
[20] VLHC Study, Ch. 5.

realizing the next stage by serving as a single turn injector for the higher field collider. Single turn injection reduces the aperture required in higher field magnets thereby reducing significantly the cost of the second step. A large diameter tunnel (~4 m) was chosen to accommodate at least two collider rings. The study has addressed the practicalities of building such a large tunnel in the geology near Fermilab and assigned a tunnel cost accordingly in consultation with tunneling experts. As one sees from Table 2, each stage is a reasonable step across the energy frontier. The study assessed the cost of the first phase of the project and did several "reality checks" of this estimate against SSC costs and TESLA cost estimates. The conclusion of the study is simple; "if we can afford a linear collider, we can afford the VLHC."

	Stage 1	**Stage 2**
Circumference (km)	233	233
C-M Energy (TeV)	40	175
Number of IRs	2	2
Peak lum. (10^{34} cm^{-2} s^{-1})	1	2
Lum. lifetime (hrs)	24	8
Injection energy (TeV)	0.9	10.0
B_{dipole} at full energy (T)	2	9.8
Ave. arc bend rad. (km)	5.0	35.0
Protons/bunch (10^{10})	2.6	0.8
Bunch Spacing (ns)	18.8	18.8
β^* at collision (m)	0.3	0.71
Free space in IR (m)	± 20	± 30
Inelastic σ_{in} (mb)	100	133
Interactions/crossing	21	58
P_{synch} (W/m/beam)	0.03	4.7
P_{ave} for collider (MW)	20	100
Installed power (MW)	30	250

Table 2. Parameter list for the VLHC study

5 The Next Step: Upgrading LHC

Presently the LHC represents the largest single investment of the world high energy physics community in energy frontier physics. For the next decade discoveries at the energy frontier will be dominated by the LHC operating in its initial configuration. Yet soon after LHC begins physics running, decisions will have to be made concerning the upgrades of the collider. One option with a large impact on ATLAS and CMS (and on the directions of future detector research) is to increase of the luminosity[21] by a factor of ten thereby increasing the mass reach of the collider by 20 – 30%.

> “This requirement can easily be seen by considering the time required to reduce the statistical errors by a factor of two. Figure 4 shows a simple model in which the first collisions in LHC take

[21] High-Energy Physics Facilities of the DOE Office of Science Twenty-Year Road Map, HEPAP report to the Director of the Office of Science, 17 March 2003.

place in 2007, the first real physics run is in 2008, and the luminosity rises slowly to reach the design value of 10^{34} cm^{-2} s^{-1} by the end of 2011. The growth of the integrated luminosity is shown, assuming an effective 10^7 seconds per year at the indicated luminosity. The statistical error on a typical measurement, which is proportional to $(\int L\,dt)^{-1/2}$, is shown in arbitrary units, as is the time required after each year to accumulate enough new data to halve the statistical error. By the time the LHC reaches the design luminosity, this "error halving time" will be at least 4-5 years. Thus, beyond about 2013-2014, the utility of additional running, without a major upgrade to the machine and detectors, will be limited."[22]

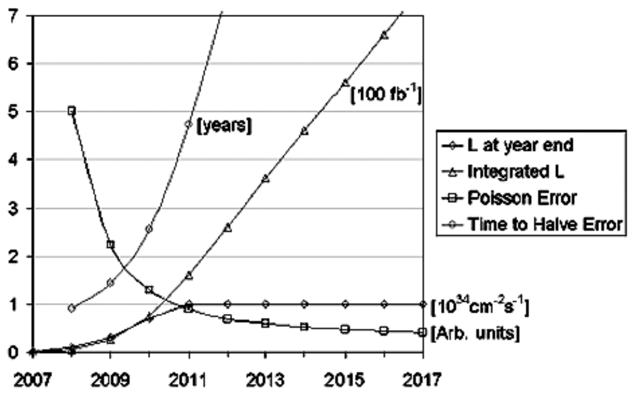

Figure 4. Results of a simple model used to estimate the time from LHC start it takes to halve the statistical error in a measurement. Note that after a year of operating at full luminosity, it will take more than seven years to halve the error.

A LHC luminosity upgrade will require upgrading or completely replacing several accelerator systems. The US LHC Accelerator Collaboration (BNL-FNAL-LBNL), which presently has responsibility for building the major components of the present high luminosity IRs, is uniquely qualified to lead in developing the new IRs and their constituent magnets. In developing its multi-year proposal to the US DOE, the LARP collaboration has considered[23] several potential configurations of the upgraded IRs.

The interaction regions (IR) must be replaced with higher performance magnets to

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[22] R. Kephart, M.J. Lamm, P. Limon, J. Marriner, T. Sen, J. Strait, A.V. Zlobin, P. Cameron, A. Drees, W. Fischer, R. Gupta, M. Harrison, F. Pilat, S. Peggs, W. Barletta, J. Byrd, P. Denes, S. Gourlay, A. Ratti, W. Turner, "The U.S. LHC Accelerator Research Program: A Proposal," May, 2003. Hereafter LARP Proposal.

[23] J. Strait, et al., Towards a New LHC Interaction Region Design for a Luminosity Upgrade, Proceedings of the US Particle Accelerator Conference, Portland OR, 12-16 May 2003. http://www-td.fnal.gov/LHC/USLARP/References/IR_Upgrades.pdf

obtain larger aperture optics with a smaller □*. Beam instrumentation, feedback systems, and accelerator diagnostics will have to be improved sufficiently to provide an undersatnding of how to deal instabilities limiting the beam current and how to assure the safety of the collider with several times the stored energy. In all the configurations considered thus far, the IR magnets would represent a considerable advance in the technology embodied in the first generation IR magnets. All require Nb_3Sn technology both to achieve the higher fields and to provide greater temperature margin against radiation heating than is available with NbTi. For example, quadrupoles require an aperture of ~ 110 mm with $G_{op} > 200$ T/m for any new IR.

> “The issues to be addressed in designing a new IR for higher luminosity[24] are reducing □*, minimizing the effects of the parasitic long-range beam-beam interactions within the region shared by the two beams, and dealing with the high radiation load that is a by-product of the very high luminosity. …The simplest case is to duplicate the existing optics and layout, but with larger aperture quadrupoles that will permit a substantial reduction in □* …. Assuming that the crossing angle scales with $(□*)^{-1/2}$, a 110 mm aperture quadrupole would allow about a factor of three decrease in □*. This layout has the virtues representing the simplest possible change to the existing layout… However, it does not address the potentially severe problem of parasitic collisions. If a larger crossing angle is required to generate greater beam separation, then □max would have to be reduced and □* increased to compensate.”[25]

Achieving the goal of having one or more quadrupole and separation dipole magnet designs ready for prototyping in 2009 –2010, requires a vigorous research program to develop Nb_3Sn magnet technology to start immediately. This work is a stepping-stone to the dipole magnets required for the next, higher energy hadron collider.

Given the formidible difficulties of dealing with 10 events/cm/crossing in an upgraded LHC, one might ask “why not increase the energy instead?” The recent test of HD-1 at 16 Tesla and the designs at LBNL for a new dipole in the range of 17 -18 T make the idea of an LHC energy doubler (LHC2) a tantalizing prospect. It is still too early in our research program to know whether dipoles for an LHC2 are practical and affordable to build. Nonetheless, we can say that LHC2 is likely to be an expensive machine; virtually the entire collider would have to be rebuilt. Therefore, the critical question is whether there is additional sufficient physics at 28 TeV to justify an expenditure that would likely be a substantial fraction of the cost of “greenfield” supercollider at significantly higher energy. Such a judgement must await first physics results form the LHC. In the meanwhile, the US program in magnet development will be exploring the limits of Nb_3Sn technology, and will be ready if the answer is in the affirmative

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[24] *Id.*
[25] LARP Proposal

6 CONCLUDING REMARK

A final remark echos continual advice from Prof. Zichichi: the public is part of the project. Taxpayers pay the cost; they must share the excitement. We can connect to the public's cosmic fascination with our search for hidden universes (extra dimensions), dark energy, and the origins of space and time. The SSC experience should teach us not to take interest of the broader physics community for granted, either. High energy physicists must articulate the intellectual excitement to those in other disciplines. In addition, perhaps they “get a piece of the facility ” (such as the X-ray FEL in the TESLA proposal). Inclusion of other scientific communities in our thinking from the beginning will maximize our chances of continuing on the exciting road of accelerator-based high energy physics.

5 ACKNOWLEDGEMENTS

Many of the concepts for the development of the high field magnet program have been formulated and discussed over the past few years at a series of Eloisatron workshops held at the Ettore Majorana Center for Scientific Culture in Erice, Sicily. I am grateful to Prof. Antonino Zichichi for his support of these meetings; he has inspired my enthusiasm for the 200 TeV frontier. In particular I would like to thank all the participants of the 39th and 43rd ELOISATRON superconducting magnet workshops for their illuminating presentations and discussions. Much of this paper is based on work of those colleagues who have been at the forefront of driving this endeavor forward. The VLHC Design Study Report has been a crucial resource; I urge everyone to read it. The constant support and encouragement of Drs. Bruce Strauss and David Sutter have made this enterprise at Berkeley possible and rewarding. I am also grateful to Prof. Luisa Cifarelli and all the staff of the Ettore Majorana Center for Scientific Culture for their hospitality during our workshops. This work was supported by the Office of High Energy Physics of the U.S. Department of Energy under Contract No. DEAC03-76SF00098.